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Nuclear physics with a medium–energy Electron–Ion Collider*

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Abstract

A polarized ep/eA collider (Electron–Ion Collider, or EIC) with variable center–of–mass energy $\sqrt{s} \sim 20 - 70$ GeV and a luminosity $\sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ would be uniquely suited to address several outstanding questions of Quantum Chromodynamics (QCD) and the microscopic structure of hadrons and nuclei: (i) the three–dimensional structure of the nucleon in QCD (sea quark and gluon spatial distributions, orbital motion, polarization, correlations); (ii) the fundamental color fields in nuclei (nuclear parton densities, shadowing, coherence effects, color transparency); (iii) the conversion of color charge to hadrons (fragmentation, parton propagation through matter, in–medium jets). We briefly review the conceptual aspects of these questions and the measurements that would address them, emphasizing the qualitatively new information that could be obtained with the collider. Such a medium–energy EIC could be realized at Jefferson Lab after the 12 GeV Upgrade (MEIC), or at Brookhaven National Lab as the low–energy stage of eRHIC.

Introduction. Understanding the internal structure of hadrons and nuclei on the basis of the fundamental theory of strong interactions, Quantum Chromodynamics (QCD), is one of the central problems of modern nuclear physics, as described in the 2007 NSAC Long–Range Plan [1]. It is the key to understanding the dynamical origin of mass in the visible universe and the behavior of matter at astrophysical temperatures and densities. It is an essential step in describing nuclear structure and reactions from first principles, with numerous applications to science and technology. Theoretical methods to apply QCD to hadronic and nuclear systems have made dramatic advances in the last two decades but rely crucially on new experimental information for further progress.

Electron scattering has been established as a powerful tool for exploring the structure of matter at the sub–femtometer level ($< 1\,\mathrm{fm} = 10^{-15}\,\mathrm{m}$). Historically, such experiments provided the first proof of the extended nature of the proton and revealed the presence of pointlike constituents, or quarks, at smaller scales, revolutionizing our understanding of strong interactions. Subsequent experiments established the validity of QCD and the presence of gluonic degrees of freedom at short distances and measured the basic number densities of quarks and gluons in the nucleon (proton, neutron). While much progress has been made, several key questions remain unanswered [1]:

I) What role do non–valence ("sea") quarks and gluons play in nucleon structure? What are their spatial distributions? How do they respond to polarization? What is their orbital motion, and how does it contribute to the nucleon spin? The answers to these questions will provide essential information on the effective degrees of freedom emerging from QCD at distances of the order of the hadronic size ($\sim 1\,\mathrm{fm}$).

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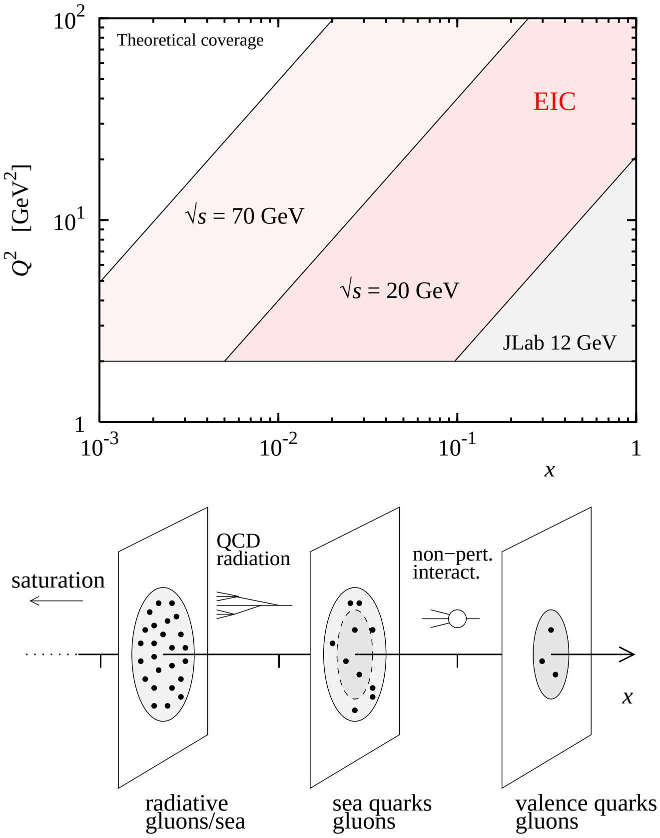
II) What are the properties of the fundamental QCD color fields in a nucleus? What are the nuclear gluon and sea quark densities? To what extent are they modified by nuclear binding, quantum–mechanical interference, and other collective effects? These questions are the key to understanding the QCD origins of nucleon interactions at different energies, the role of non–nucleonic degrees of freedom, and the approach to a new regime of high gluon densities and saturation at high energies.

III) How do colorless hadrons emerge from the colored quarks and gluons of QCD? What dynamics governs color neutralization and hadron formation? By what mechanisms does the color charge of QCD interact with nuclear matter? We are still far from understanding the strong interaction dynamics of the fundamental process of conversion of energy into matter.

It is now widely accepted that a polarized ep/eA collider (Electron–Ion Collider, or EIC) with a variable ep center–of–mass (CM) energy in the range $\sqrt{s} = 20 - 70\,\text{GeV}$, and a luminosity of $\sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ over most of this range, would offer a unique opportunity to address these questions [2]. Such a facility would provide the necessary combination of kinematic reach (resolution scale, energy span), luminosity (precision, multi–dimensional binning, rare processes), and detection capabilities (resolution, particle identification) to study nucleon and nuclear structure through scattering experiments with a variety of final states. It would represent the natural next step after the high–luminosity fixed–target ep/eA experiments (JLab 12 GeV, SLAC) and the high–energy HERA ep collider (protons only, unpolarized). It would be the first ever high–energy electron–nucleus collider and open up qualitatively new possibilities to study QCD in the nuclear environment. Finally, polarized beams would allow one to investigate proton and neutron spin structure with unprecedented accuracy and kinematic reach; such measurements were so far possible only in fixed–target experiments (EMC, SMC, SLAC, HERMES, COMPASS, JLab) or polarized pp collisions (RHIC). In the following we summarize what measurements with such a medium–energy EIC could contribute to answering the above questions. Nuclear physics at higher energies and possible studies of electroweak interactions with an EIC are described in Ref. [2].

Three–dimensional structure of the nucleon in QCD. The nucleon in QCD represents a dynamical system of fascinating complexity. In the rest frame it may be viewed as an ensemble of interacting color fields, coupled in an intricate way to the vacuum fluctuations that govern the effective dynamics at distances $\sim 1\,\text{fm}$. In this formulation its properties can be studied through large–scale numerical simulations of the field theory on a discretized space–time (Lattice QCD) [3] as well as analytic methods. A complementary description emerges when one considers a nucleon that moves fast, with a momentum much larger than that of the typical vacuum fluctuations. In this limit the nucleon's color fields can be projected on elementary quanta with point–particle characteristics (partons), and the nucleon becomes a many–body system of quarks and gluons. As such it can be described by a wave function, in much the same way as many–body systems in nuclear or condensed matter physics (see Fig. 1). In contrast to these non–relativistic systems, in QCD the number of pointlike constituents is not fixed, as they constantly undergo creation/annihilation processes mediated by QCD interactions, reflecting the essentially relativistic nature of the dynamics. A high–energy scattering process takes a "snapshot" of this fast–moving system with a spatial resolution given by the inverse momentum transfer $1/Q$. The energy transfer, parametrized by the Bjorken variable x, defines the momentum fraction of the struck constituent and thus determines what particle configurations are intercepted in the scattering process. In this way one can probe in detail the various components of the wave function and map out their properties (see Fig. 1). Measurements with JLab 12 GeV probe nucleon structure in the region dominated by the valence quark component ($x > 0.1$), including the unknown $x \to 1$ region [4].

In addition to the valence quarks, the nucleon contains a "sea" of quark–antiquark pairs that is created by non–perturbative QCD interactions and reflects the complex structure of the ground state (or vacuum) of the theory. The spin and flavor quantum numbers carried by the sea sit mainly in the region $0.01 \lesssim x < 0.1$ and are poorly constrained by present data. A medium–energy EIC could measure the distribution of sea quarks through semi–inclusive measurements,



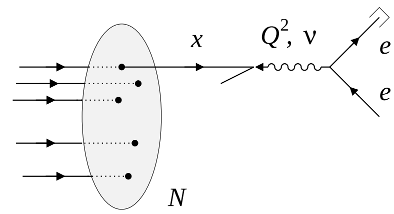


Figure 1: *Top right:* Deep–inelastic electron–nucleon scattering. The momentum transfer Q^2 defines the resolution scale, the Bjorken variable x is the momentum fraction of the constituents probed in the scattering process, and $\nu = Q^2/(2Mx)$ determines the boost imparted to the struck quark and the hadrons emerging from its fragmentation. *Top left:* Kinematic coverage in x and Q^2 with JLab 12 GeV and a medium–energy EIC ($\sqrt{s} = 20$ and 70 GeV), for $Q^2_{\text{min}} = 2\,\text{GeV}^2$. *Bottom left:* Components of the nucleon wave function probed in scattering experiments at different x (see axis on graph).

in which the charge and flavor of the struck quark/antiquark are "tagged" by detecting hadrons $(\pi^\pm, K^\pm, p, \bar{p}, \ldots)$ produced from its fragmentation. Compared to fixed–target experiments, the energy available with the collider ensures that the hadronization of the struck quark proceeds independently from the target remnants and cleanly preserves the original spin–flavor information. The kinematic coverage and detection capabilities are uniquely suited to such measurements, allowing for a precise mapping of this largely unexplored component of the nucleon.

Equally important is the distribution of polarized gluons in the nucleon. Besides its intrinsic importance, its measurement is needed to solve the "puzzle" of the nucleon spin decomposition and quantify the role of orbital angular momentum in the nucleon wave function. Since gluons carry no electric charge, electromagnetic scattering can probe them only indirectly, through the Q^2 dependence of the nucleon structure functions. Present eN data, together with those from polarized pp collisions at RHIC, practically do not constrain the polarized gluon density for $x \lesssim 0.05$. Inclusive measurements with a medium–energy EIC would dramatically extend the data set and determine the polarized nucleon structure function $g_1(x, Q^2)$ down to $x \sim$ few $\times\, 10^{-3}$ with a substantial range in Q^2 (see Fig. 1), allowing one to extract the polarized gluon density from the Q^2 dependence [5].

Other fundamental characteristics of the nucleon are the transverse spatial distributions of quarks and gluons carrying a certain momentum fraction x (see Fig. 2). They define the basic size and "shape" of the nucleon in QCD and convert the one–dimensional picture conveyed by the longitudinal momentum densities into a full three–dimensional image of the fast–moving nucleon [6]. Information on the transverse distribution of quarks and gluons is obtained from exclusive scattering $\gamma^* N \to M + N\,(M = \text{meson}, \gamma, \text{heavy quarkonium})$. Such processes probe the generalized parton distributions (GPDs), which combine the concept of the quark/gluon momentum density with that of elastic nucleon form factors. Measurements of J/ψ photo/electroproduction with a medium–energy EIC would be able to map the transverse spatial distribution of gluons in the nucleon above $x \sim$ few $\times\, 10^{-3}$ in unprecedented detail. In particular, these measurements would

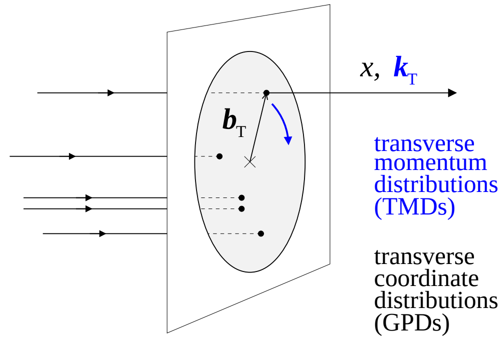


Figure 2: Three–dimensional structure of the fast–moving nucleon in QCD. The distribution of partons (quarks, gluons) is characterized by the longitudinal momentum fraction x and the transverse spatial coordinate $\boldsymbol{b}_T$ (GPDs). In addition, the partons are distributed over transverse momenta $\boldsymbol{k}_T$, reflecting their orbital motion and interactions in the system (TMDs). Polarization distorts both the spatial and momentum distributions. Note that $\boldsymbol{b}_T$ and $\boldsymbol{k}_T$ are not Fourier conjugate; a joint description in both variables can be formulated in terms of a Wigner phase space density. Observables sensitive to either $\boldsymbol{b}_T$ or $\boldsymbol{k}_T$ help to establish a three–dimensional dynamical picture of the nucleon in QCD.

cover the unexplored gluons in the valence region at $x \gtrsim 0.1$, whose presence has been inferred from global fits to deep–inelastic scattering data but has rarely been confirmed directly; their dynamical origins are one of the outstanding questions of nucleon structure in QCD. Information on the transverse spatial distribution of gluons is needed also to describe the final states in pp collisions at LHC (underlying event in hard processes, multiparton processes) and understand the approach to the regime of high gluon densities at small x (initial conditions for non–linear QCD evolution equations) [7]. Measurements of real photon production (γ, deeply virtual Compton scattering) with an EIC would differentiate gluon and quark spatial distributions and study how the latter are deformed in a transversely polarized nucleon. Production of light mesons with charge/isospin (π, K, ρ, K^*) would map the transverse distributions of sea quarks and provide additional insight into their dynamical origins. This program of "quark/gluon imaging" requires differential measurements of low–rate processes and relies crucially on the high luminosity provided by the EIC in the envisaged energy range, and the possibility to longitudinally and transversely polarize the proton beam.

Closely related is the question of the orbital motion of quarks and gluons and its role in nucleon structure (see Fig. 2). This information is encoded in the transverse momentum distributions (TMDs) and their response to nucleon and quark/gluon polarization [8]. They provide a three–dimensional representation of the nucleon in momentum space, complementing the spatial view offered by the GPDs. The TMDs can be measured in semi–inclusive scattering processes $\gamma^* N \rightarrow h + X$, where particles produced by fragmentation of the struck quark ($h = \pi, K, J/\psi$, open charm), as well as the nucleon fragments, can reveal the quark and gluon transverse momentum and its correlation with the nucleon spin. The various structure functions, each of which describes certain facets of nucleon structure (transverse motion and deformation, spin–orbit correlations, orbital angular momentum, final–state interactions of the struck quark with the color fields in the nucleon) can be separated by measurements with different combinations of beam and target polarizations, including transverse nucleon polarization easily available with the collider. Measurements with a medium–energy EIC will be able to precisely determine, *e.g.*, the valence and sea quark Sivers function sensitive to spin–orbit interactions in the region $x > 0.01$, where it is expected to be sizable. They will also study for the first time the Q^2 evolution of TMDs and the region of large transverse momenta, $k_T \gg 1\,\text{GeV}$, where TMDs can be related to multiparton correlations in the nucleon. Measurements with open charm and J/ψ mesons in the final state can directly probe the gluon TMDs. All these studies require multi–dimensional binning in x, Q^2, and the energy fraction z and transverse momentum P_T of the produced meson, which can be performed only with high–statistics data as would become available with the planned EIC luminosity.

Color fields in nuclei. A basic quest of nuclear physics is to understand the structure and dynamics of the QCD color fields in nuclei with nucleon number $A > 1$. Information on these fields is obtained by studying the scattering of small–size probes — *e.g.*, a virtual photon with $Q^2 \gg 1\,\text{GeV}^2$ — from nuclei over a range of incident energies (see Fig. 3). Of particular interest is

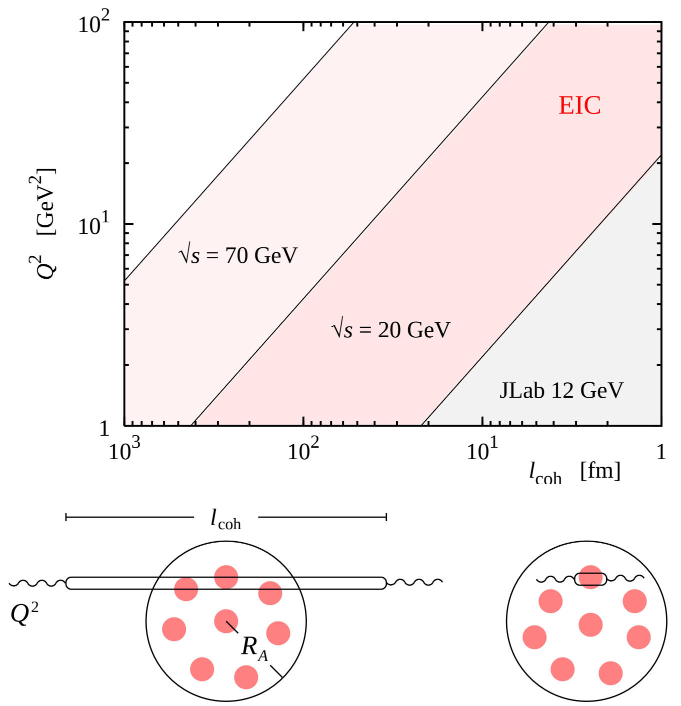


Figure 3: *Top:* Kinematic coverage in the typical coherence length $l_{\mathrm{coh}} = (M_N x)^{-1}$ and the scale Q^2 in electron–nucleus scattering with a medium–energy EIC. *Bottom:* Interaction of a small–size probe with a nucleus. The coherence length defines the lifetime of the probe in the rest frame of the nucleus, *i.e.*, the longitudinal extent of the interaction region. If $l_{coh} \ll R_A$ the interaction is mainly with the color field of a single nucleon, possibly modified by nuclear binding (*bottom right*). If $l_{coh} \gtrsim R_A$ the probe can interact coherently with the color fields of all nucleons located at the transverse position of impact (*bottom left*).

how the nuclear fields differ from the sum of the color fields of the individual nucleons. The lifetime of the probe in the target rest frame is defined by the coherence length, $l_{\mathrm{coh}} \propto (xM_N)^{-1}$, where the coefficient depends on the size of the probe but is typically of order unity. If the coherence length is much smaller than the nuclear radius $R_A \sim$ few fm, the scattering involves only a single nucleon in the nucleus. In this regime the results can be interpreted in terms of a modification of single–nucleon structure through nuclear binding and reveal the QCD origins of the nucleon–nucleon interaction. If the coherence length becomes comparable to or larger than the nuclear radius, $l_{\mathrm{coh}} \gtrsim R_A$, the color field seen by the probe is the quantum–mechanical superposition of the fields of the individual nucleons, resulting in a rich spectrum of coherence effects such as shadowing [9], diffraction, and eventually the approach to the unitarity limit (saturation) at high energies [10]. In addition, the fields change with the energy and the resolution scale Q^2 as a result of QCD radiation. An EIC with a CM energy in the range $\sqrt{s} \sim 20 - 70\,\mathrm{GeV}$ would for the first time provide the coverage in l_{coh} and Q^2 necessary to observe these phenomena, opening up a whole new area of study.

Much interesting information already comes from the basic quark and gluon densities of nuclei. A peculiar pattern of nuclear modifications was observed in fixed–target experiments and caused much excitement; it shows suppression compared to the free nucleon for $0.2 < x < 0.8$ (the famous "EMC effect," to be explored further with JLab 12 GeV), some signs of enhancement for $0.05 < x < 0.2$, and significant suppression at smaller x ("shadowing") [11]. However, such experiments were unable to reach deep in the shadowing region, distinguish valence and sea quarks, or probe gluons. Nuclear deep–inelastic scattering with a medium–energy EIC would for the first time allow one to determine the gluon and sea quark densities in a range of nuclei. Thanks to the wide kinematic coverage, the EIC will be able to penetrate deep into the shadowing region, while simultaneously having sufficient Q^2 range to extract the nuclear gluon densities through the Q^2 dependence of the structure function F_2^A at both small and large x. Measurements at different energies would isolate the longitudinal structure function F_L^A, which provides direct access to gluons. Using a combination of inclusive measurements and gluon tagging through charm production, an EIC will be able to explore nuclear gluons also in the antishadowing and EMC effect regions — a step that might prove as revolutionary for our understanding of nuclei as the discovery of the quark EMC effect 30 years ago.

Further information on the nuclear modification of the quark/gluon structure of the proton and the neutron can be gained from deep–inelastic measurements with detection of the spectator system of $A-1$ nucleons in the final state. In particular, scattering from the deuteron with a tagged spectator proton can measure the structure functions of the bound neutron at controlled virtualities, from which the free neutron quantities can be obtained by extrapolation to the on–shell point. Measurements with a tagged spectator neutron, which are extremely difficult with a fixed target but feasible with a collider using a zero degree calorimeter, provide completely new information on the bound proton structure functions that constrains theoretical models of binding effects and the on–shell extrapolation (contrary to the neutron, the free proton structure function is known from independent measurements with a proton target). Tagged measurements on heavier nuclei could explore the effects of nucleon embedding in a complex nuclear environment. Measurements of coherent nuclear scattering, in which the nucleus remains intact and is detected with a small recoil momentum of $\lesssim 100\,\mathrm{MeV}$ in the final state, can map the transverse gluonic radius of nuclei and study shadowing as a function of the impact parameter — information essential for the analysis of high–energy pA and AA collisions.

Experiments with nuclear targets also provide qualitatively new insight into the short–distance dynamics of deep–inelastic processes. A fundamental prediction of QCD as a gauge theory is color transparency: the interaction of small–size colored configurations with hadronic matter is governed by their color dipole moment and vanishes proportionally to their transverse size. A medium–energy EIC would allow one to test this prediction through measurements of meson electroproduction on nuclei over a wide range of l_{coh} and Q^2, controlling the longitudinal extent of the interaction region and the transverse size of the $q\bar{q}$ configuration. Previous fixed–target measurements (E665, HERMES) could not vary these parameters fully independently.

Detailed studies of color transparency and a reliable determination of the nuclear gluon density in the shadowing region $0.001 < x < 0.1$, as envisaged with a medium–energy EIC, are essential also for a quantitative assessment of the approach to the saturation regime at small x. In this regime the transverse density of gluons interacting with a high–energy probe becomes so large that it constitutes a new dynamical scale that can serve as the basis for systematic calculations of inclusive cross sections as well as final–state characteristics [10]. Saturation dynamics is expected to be important in AA and central pp collisions at the LHC and has been associated with phenomena observed in heavy–ion collisions at RHIC. Nuclear shadowing, as would be established with a medium–energy EIC, may slow down the approach to gluon saturation at small x [9]. The study of the saturation regime proper will be the object of high–energy colliders such as a high–energy EIC (eA) or the LHeC (ep and eA, see below). This program would involve measurements of inclusive and diffractive nuclear structure functions at small x, analysis of final states in which the saturation scale could manifest itself directly (*e.g.*, p_T spectra of leading forward particles), and measurements of multiparticle correlations sensitive to the dynamics of the radiation processes generating the dense gluon medium.

Emergence of hadrons from color charge. The emergence of colorless hadrons from the elementary color charge produced by short–distance probes — the so–called hadronization process — is a principal aspect of QCD which still lacks a quantitative understanding from first principles [12]. Empirical fragmentation functions, which encode the probability that a quark or gluon decays into a hadron and colored remnant, have been obtained by fitting experimental data, but knowledge of the underlying dynamics remains sketchy and model–dependent. Basic questions concern even the characteristic time scales for the neutralization of color charge (sometimes referred to as pre–hadron formation) and the formation of physical hadrons (see Fig. 4). Measuring these time scales would be the first step toward understanding how hadrons emerge dynamically from the color charge of QCD, complementing the information obtained from hadron structure and spectroscopy studies.

Nuclear deep–inelastic scattering provides a known and stable nuclear medium ("cold QCD matter") and a final state with good experimental control of the kinematics of the hard scattering. This permits one to use nuclei as femtometer–scale detectors of the hadronization pro-

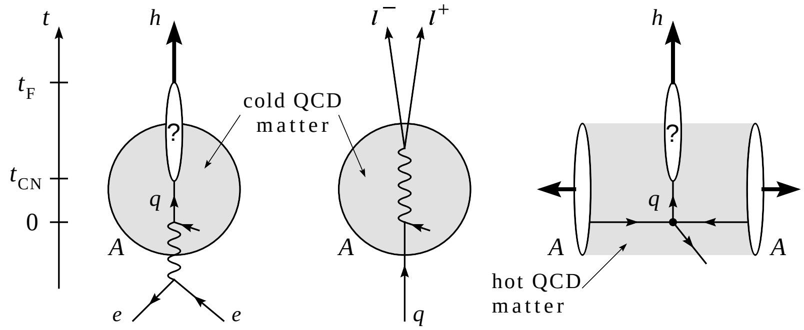


Figure 4: Parton propagation and hadronization in cold and hot nuclear matter. The color neutralization ($t_{\rm CN}$) and hadron formation ($t_{\rm F}$) time scales are indicated on the vertical time axis.

cess (see Fig. 4). By measuring the energy loss and transverse momentum broadening of leading hadrons induced by the nuclear environment one can discriminate the different dynamical processes (medium–induced gluon bremsstrahlung, pre–hadron reinteraction) and infer the space–time evolution of hadronization. Theoretical models of these processes can be calibrated in eA scattering and then applied to study, *e.g.,* the Quark–Gluon Plasma created in high–energy nucleus–nucleus collisions ("hot QCD matter," see Fig. 4). The combination of high energy and luminosity offered by the EIC promises a truly qualitative advance in this field, compared with current and planned fixed target experiments. The large Q^2 range permits measurements in the fully calculable perturbative regime with enough leverage to determine nuclear modifications in the QCD evolution of fragmentation functions; the high luminosity permits the multidimensional binning necessary for separating the many competing effects and for detecting rare hadrons. The large energy range $\nu \approx 10 - 1000\,\text{GeV}$ allows one to experimentally boost the hadronization process in and out of the nuclear medium, in order to cleanly extract the color neutralization and hadron formation times (small ν) and isolate in–medium parton propagation effects (large ν). The quark and gluon in–medium energy loss measured in this way is of major interest in its own right, as it addresses the fundamental question of the interaction of an energetic color charge with hadronic matter in QCD. With an EIC one will be able for the first time to study also the in–medium propagation and hadronization of heavy quarks (charm, bottom) in eA collisions, which is necessary to test predictions for their energy loss and confront puzzling measurements of heavy flavor suppression in the Quark–Gluon Plasma at RHIC.

Furthermore, an EIC with $\sqrt{s} \gtrsim 30$ GeV will permit for the first time to measure jets and their substructure in eA collisions. The modifications compared to jets in ep scattering in the same kinematics can be related to the propagation of the colored parton shower in the nuclear medium and offers new insight into its space–time evolution. It can also be used to measure the cold nuclear matter transport coefficients which encode basic information on the non–perturbative gluon fields in nuclei.

Another interesting aspect of hadronization is the evolution of the system from which a color charge has been removed by the hard process. In deep–inelastic ep scattering with an EIC at $\sqrt{s} \sim 20 - 70\,\text{GeV}$ one would for the first time be able to cleanly separate the virtual photon (or current) and target fragmentation regions in the final state and study the properties of the latter using forward detectors. In this way one could follow the materialization of the "color hole" in the nucleon created by the hard process. Measurements of particle correlations between the current and target fragmentation regions (*e.g.*, particles originating from s and $\bar{s}$ quarks) would provide new insight into the nucleon's spin–flavor structure and could reveal dynamical pair correlations in the nucleon's partonic wave function, as are expected to be induced by the dynamical breaking of chiral symmetry in the QCD vacuum.

Possible realizations of a medium–energy EIC. Two scenarios for the realization of a medium–energy EIC of $\sqrt{s} \sim 20 - 70\,\text{GeV}$ are presently being discussed. The design proposed

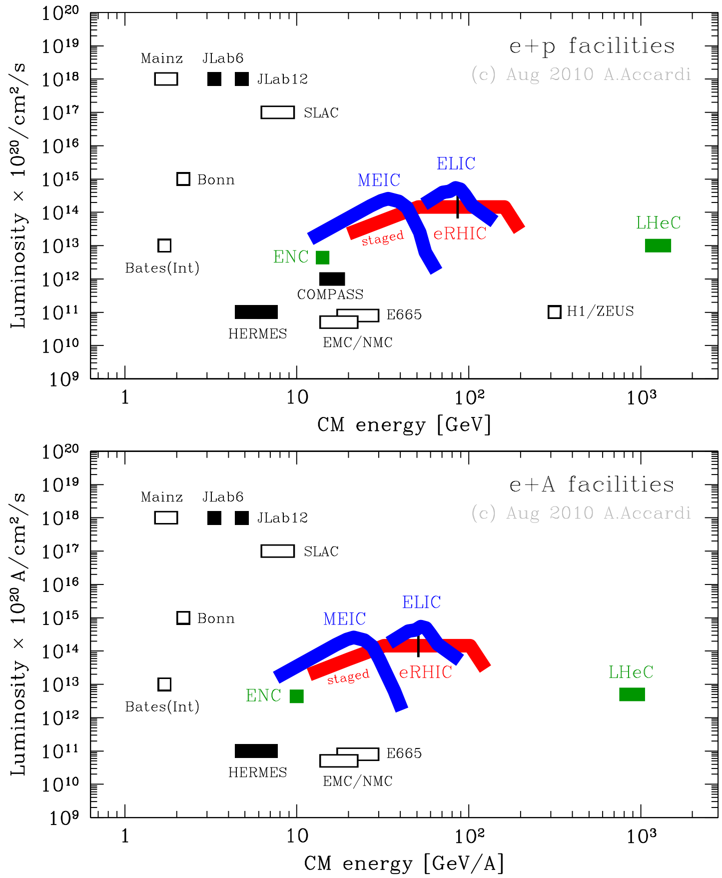


Figure 5: Projected luminosity for *ep* (top) and *eA* (bottom) collisions as a function of the CM energy per nucleon for the JLab (MEIC, ELIC; blue) and BNL (eRHIC; red) designs as of August 2010 [13, 14]. Also shown are the values achieved by existing and past *ep*/*eA* facilities, as well as the projections for the planned *ep*/*eA* collider at CERN (LHeC) [15] and the low–energy *ep* collider at GSI (ENC) [16].

by Jefferson Lab (MEIC) would use the 11 GeV CEBAF electron accelerator and a newly built ion complex as injectors for a ring–ring *ep*/*eA* collider with energies $E_e = 3 - 11\,\mathrm{GeV}$ and $E_p = 20 - 100\,\mathrm{GeV}$ and a circumference of $\sim 1\,\mathrm{km}$, slightly smaller than that of the present CEBAF accelerator. This design would achieve a luminosity of the order of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ over a broad range of CM energies. The ring is laid out in the form of a Figure–8 for optimal polarization transport and could support up to four interaction points. A high–energy collider of $\sqrt{s} \sim 70 - 100\,\mathrm{GeV}$ (ELIC) could be realized as an upgrade with a larger ring of $\sim 2.5\,\mathrm{km}$. The design proposed by Brookhaven National Lab (eRHIC) would use the proton/ion beam of RHIC with energy up to 325 GeV and collide it with a 5 GeV electron beam accelerated by energy–recovering linacs placed along a new recirculating ring in the RHIC tunnel. Higher CM energies could be realized by increasing the electron energy from 5 to 20 (possibly 30) GeV through addition of superconducting radio–frequency cavities to the linacs ("staging"). Figure 5 shows the projected luminosity for *ep* and *eA* collisions as a function of the CM energy per nucleon for both designs (the figures shown here reflect the status of the designs as of August 2010 and were the basis for the physics simulations compiled in Ref. [2]). Comparison with the values achieved with existing or past *ep*/*eA* facilities shows that a medium–energy EIC would dramatically extend the combined "energy × luminosity" frontier, enabling the next–generation nuclear physics experiments described in this summary. Details of the accelerator designs and further information can be found in Ref. [13, 14].

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